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Impact on wind turbine loads from different down regulation control strategies

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Abstract. This paper presents a study on derating wind turbine power levels in a wind farm and the associated loads on down wind placed wind turbines. This is done by derating the wind farm power output for certain periods of time. Derating can be done in different ways by adjusting the rotor speed and blade pitch on the individual turbines which also has a direct impact on the turbine component loads. The paper studies three characteristic derating strategies on the upstream wind Turbine (WT) and the corresponding load impact on the downstream one. These are defined as minimum/maximum rotor speeds (minRS, maxRS) and minimum thrust (minT) modes. Derating factors of 20% and 40% on available power are applied together with 4 and 7 diameters WT interspace. The study is based on aeroelastic simulations of a 2MW generic WT model including wake effects. The results show that below rated wind speed (8m/s) the downstream WT blade flap fatigue loads are minimized when the upfront WT is derated with the minRS or minT strategy. The maxRS mode returns around 2% percent higher loads. The load levels for minRS and minT strategies are almost equal. Above rated wind speed (16m/s) the trend is the same as at 8m/s with a bit higher difference on load levels, up to 6% percent at tighter interspace bewteen maxRS strategy and the other two. The fore-aft fatigue loads on the tower base and the main bearing yaw moment follow the same trends as the blade for both below and above rated wind speed.

Finally, it is also found that there is a correlation on the load levels and the wind deficit values. In all cases up to around ±10 degrees incoming wind direction the wake deficit from the maxRS control strategy is higher and the load levels follow the same trend. This is an important outcome and links the control strategies directly to the wake deficit due to the upstream WT operation.

1. Introduction

As wind energy contributes more in the total electricity production, the grid operators demand less amount of delivered energy than the available for certain periods of time. This is done by derating the wind farm power output. Derating can be done in different ways by adjusting the rotor speed and blade pitch angle on the individual turbines, which affect the fatigue loads on the turbine components. Until know the main focus has been on power optimization [10, 9, 8, 1] and there has been limited documentation on the load variations as a result of different down-regulation strategies on wind turbines under wakes. A paper from Schaak [11] has investigated WT control strategies in a wind farm configuration and load effects, but essentially it does not account for the complex wake structures that contribute to the fatigue of the WT components. A very recent study from Kanev et al [2] investigates both wind farm loads and power on derating operation by applying pitch-based active wake control (AWC) and yaw based AWC. It is concluded that the lifetime extension due to load alleviation is at least 1% and 1.5% respectively, which is a promising outcome. This paper studies the load impact for three characteristic derating strategies on the upstream wind Turbine (WT) to the downstream one using a high fidelity engineering model for the wake effects. The strategies are defined as minimum/maximum rotor speeds (minRS, maxRS) and minimum thrust (minT) modes. The essential idea behind the study is that the wake strength in a downstream position depends on a variety of parameters making it non-trivial to find the best approach. For closely spaced turbines the strength of the initial upstream deficit is probably of highest importance whereas the turbulent mixing has a biggest impact for larger inter-spacing distances. Differences in rotor speed and blade pitch angle create a changed load distribution over the rotor also impacting differently on the downstream turbine. The analysis is based on high fidelity aeroelastic simulations using the HAWC2 code [3] together with the Dynamic Wake Meander (DWM) model which has been validated in wind turbine load predictions under wakes [5, 6, 7]. The selected operation set points are constrained by the boundaries of the load envelope under normal power production. Analyses are performed at four and seven WT diameter interspaces and an ambient wind direction range of ± 15 degrees. Additionally, derating factors of 20% and 40% on available power are applied.

2. Theoretical Background

2.1. Wind turbine loads under wakes

Downstream WTs in wind farm configurations are affected in terms of fatigue damage by the chosen operating control strategy and the wake effects of the upfront operating turbines. Many models have been developed in order to capture the wind speed deficit and the increased turbulence due to the generated wakes. The DWM model is used in this study which is implemented in HAWC2. The wake deficit is extracted from the Blade Element Momentum (BEM) theory together with the boundary layer approximation of the Navier-Stokes equations. The updated DWM model [4] takes into account the contribution of the nearest upstream WT wake up to rated ambient wind speeds where as all upstream wakes are included for wind speeds above rated.

The DWM model which is currently implemented in HAWC2 utilizes the rotor speed and blade pitch angle to capture the wake propagation to the downstream WT. These values affect the created velocity deficit and turbulence mixing downstream. The WTs can operate at different combinations of rotor speed and blade pitch angle during down-regulation which has different impact on total thrust and thus the generated wakes can be altered in such a way for fatigue load alleviation.

2.2. Down regulated wind turbine control

As was described in the previous paragraph the rotor speed and blade pitch angle of the upstream WT are important parameters that are involved in the computation of the wake strength and path downstream. The WTs under normal power production are tuned for power output optimization below rated wind speed and for limitation of the loads and power above rated. In Figure 1 are plotted the rotor speed, the blade pitch angle and the electrical power from cut-in to cut-out for a typical 2MW WT. The values are normalized by their maxima. Three distinct regions exist, the first is the variable rotor speed (also known as partial load region), the second 'region 2' with constant rotor speed and 'region 3' with constant rotor speed and power (also known as full load region). In region 1 the pitch angle is kept optimum and the rotor speed is adjusted for power maximisation (optimum tip speed ratio). In the second region the generator torque is adjusted for rotor speed regulation to the rated while pitch angle is still optimum. Finally, in the third region the power and the rotor speed are kept constant to their rated values by pitching the blades. When the WT is down-regulated these rotor speed and pitch angle set points are not unique. As it is shown in this study different combinations of set points can lead to the same power limitation but different WT load levels. Transient loads of switching from the partial load region to the full load region are however not included in this study. In the future is also planned the study of the load levels on the downstream turbine during down regulation operation.

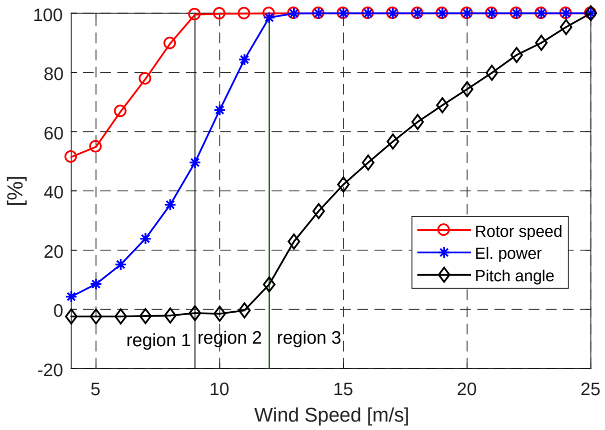

Figure 1. Rotor speed, pitch angle and electrical power curves as a function of wind speed under normal power production for a typical variable speed and pitch wind turbine. The values have been normalized by their maxima.

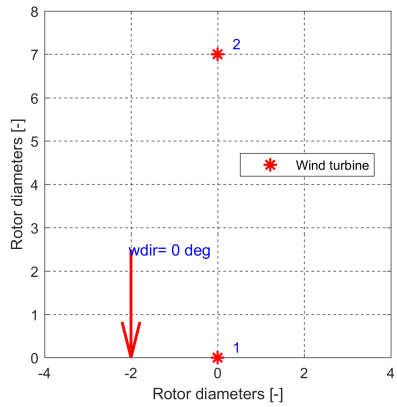

Figure 2. Wind farm layout. Free-stream upfront WT-2 is down-regulated, while downstream WT-1 is under normal operation but exposed to wake effects.

3. Simulations Set-up

3.1. Wind turbine model

The analysis is based on high fidelity aeroelastic simulations in time domain using the HAWC2 code. The key parameters of the WT aeroelastic model are summarized at Table 1. The model consists of the tower fixed to the ground, the nacelle, the main shaft, the hub and the blades. The 1 Hz equivalent fatigue loads on the blade root, the tower base and nacelle yaw bearing are evaluated for the downstream WT (WT-1). The equivalent loads are extracted applying rain-flow counting on the time series outputs. Wöhler exponents of 12, 4 and 8 are chosen for the blade, the tower and the nacelle yaw bearing respectively.

3.2. Wind farm set-up

For the purpose of this study a simple wind farm layout is assumed with two WTs (Figure 2), where the upstream WT (WT-2) is down-regulated by 20% and 40% on available power. The fatigue loads on the downstream WT (WT-1) are evaluated for different incoming wind directions (wake angles). The downstream WT is set-up to operate under normal power production without any power curtailment. Furthermore, two WT interspaces are evaluated, four and seven wind turbine Diameters (4D, 7D), which correspond to a rather tight wind farm layout similar to Lillgrund wind farm with interspaces down to 3.3D and 7D such as the Horns Rev1 minimum interspace. Two incoming wind velocities are investigated per case 8 m/s (below rated) and 16 m/s (above rated). The ambient wind direction is varied within ±15 deg with increments of 1 degree. There is no yaw misalignment, in other words the WTs are assumed to be aligned with

Table 1. Key parameters of the WT aeroelastic model.

Parameter	Value
Rotor Orientation	Clockwise rotation - Upwind
Control	Variable speed and collective pitch
Controller	DTU controller
Number of blades	3
Rotor diameter	80 m
Rated electrical power	2 MW
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Hub-height	69 m
Rotor pre-cone angle	2 deg
Shaft tilt angle	6 deg

the mean ambient wind direction. The wind shear profile follows the power law with exponent of 0.14 [-] and the ambient turbulence intensity is set to 6.5%. These values are assumed typical for offshore wind farms. A summary of the wind farm set-up is given at Table 2.

Table 2. Wind farm set-up.

Parameter	Value
Number of WTs	2
WT interspace	4D and 7D
Ambient wind speed	8 and 16 m/s
Ambient turbulence intensity	6.5 %
Wind shear profile	Power law
Wind shear exponent	0.14
Ambient wind direction	±15 degrees, step of 1 deg

3.3. Wind Farm control

Three characteristic control scenarios of power limitation are applied to WT-2 based on different set-points of rotor speed and blade collective pitch angle:

- Minimum rotor speed (minRS)
- Maximum rotor speed (maxRS)
- Minimum rotor thrust (minT)

Figure 3 shows maps of the WT aerodynamic power, thrust and tip speed ratio (TSR) at 8 m/s wind speed for different pitch angle and rotor speed sets. The possible WT operational set points for 20% and 40% down-regulation on available power are depicted by blue and black points respectively, while the set point of no derating operation is illustrated with a black cross. The selected operation set points are constrained by the boundaries of the WT load envelop under normal power production. From these maps the three control scenarios set-points are selected.

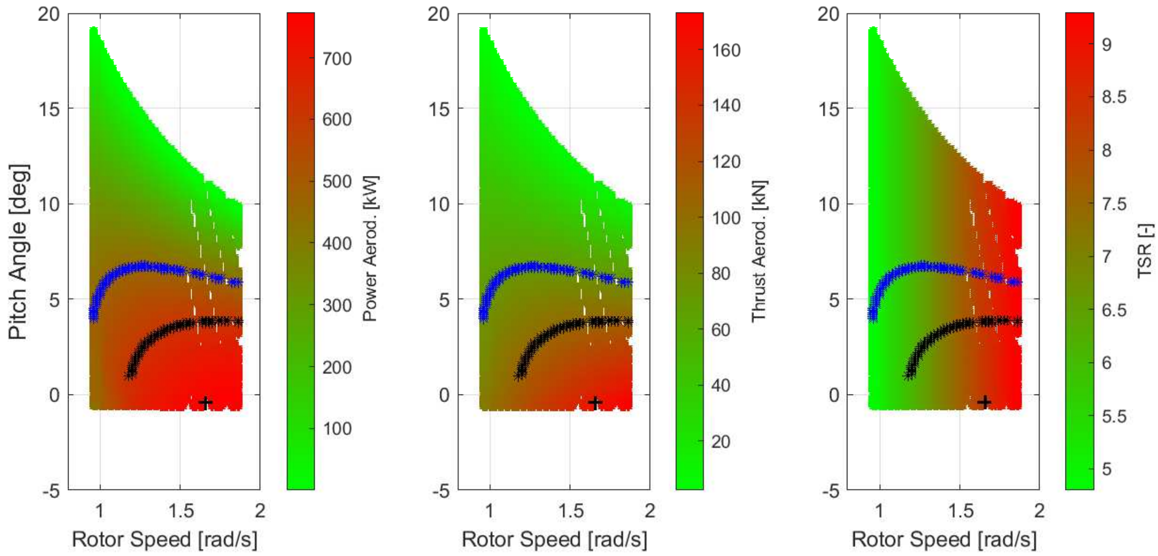

Figure 3. Maps of the WT aerodynamic power, thrust and tip speed ratio (TSR) as a function of pitch angle and rotor speed at 8 m/s wind speed. The possible set points for power down-regulation by 20% and 40% are marked with black and blue dots respectively. The set point of no derating operation is illustrated with a black cross.

4. Results

The same colors and symbols are used in the result figures as follow: The minRS and maxRS modes are illustrated with blue and red dots respectively, while the minT mode with green. For reference are also given the results without power curtailment with black crosses. The load levels have been normalised by the wake free loads at each wind speed.

The equivalent 1 Hz fatigue blade root flapwise bending moments (BM) are plotted in Figure 4 as a function of wake angle for the different operation modes at 8 m/s free wind speed (below rated). The left subplots correspond to 7D turbine interspace while the right to 4D. The upper row of subplots depicts the results of 20% and the lower of the 40% derating. It is found that with the minRS and minT modes the loads are almost equal and lower compared to maxRS mode for wake angles of up to ±10 degrees for all the cases. The load levels for the large interspace (7D) are reaching the free wake levels around ±10 degrees, while for the tight interspace (4D), the maxRS mode load levels are still higher compared to the other two modes load levels. The normalized fatigue loads are up to 4% higher for maxRS mode compared to the other two.

The asymmetric load pattern between positive and negative wind directions which is mainly seen around 'humps' is due to the interaction with half-wake deficit and the tilt angle of the downstream turbine.

The equivalent fatigue tower base fore-aft BM and nacelle yaw moment as a function of wake angle at 8 m/s free wind speed are plotted in Figures 5 and 6. Both tower base fore-aft BM and nacelle bearing yaw moment are smaller in the case of the minRS mode up to the point where the wake effects are present. Like the blade flapwise loads at 7D interspace with 20% down-regulation the load variations between the different modes are small but increase slightly as the interspace reduces to 4D.

As the blade loads, there is a small asymmetry in the tower loads which is mainly seen around humps while the nacelle yaw moment has a more irregular pattern. This is because the tower in fore aft direction feels the combined load from all the blades while the nacelle yaw moment is

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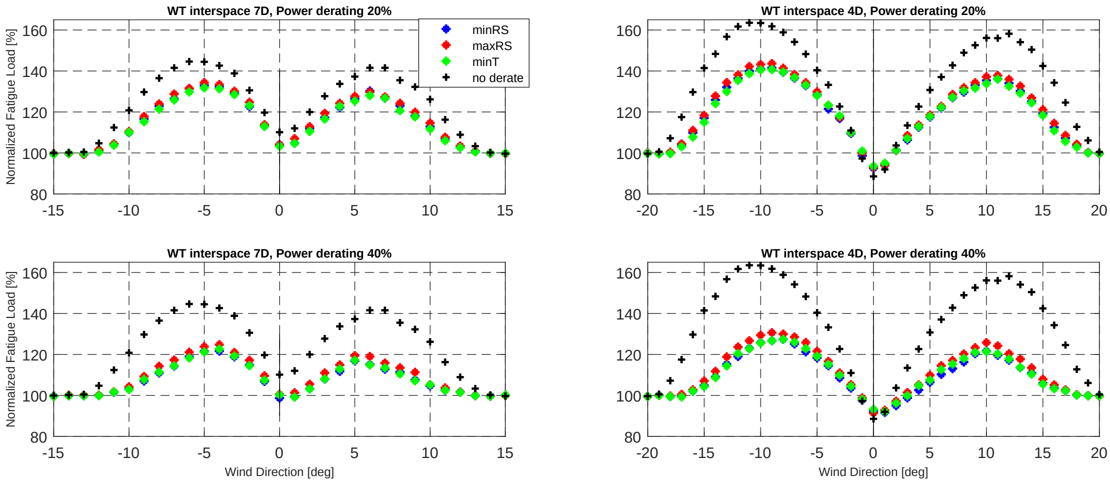

Figure 4. Equivalent 1Hz fatigue blade root flapwise BM at 8 m/s free wind speed. The loads are normalized by the wake free WT loads at the same wind speed.

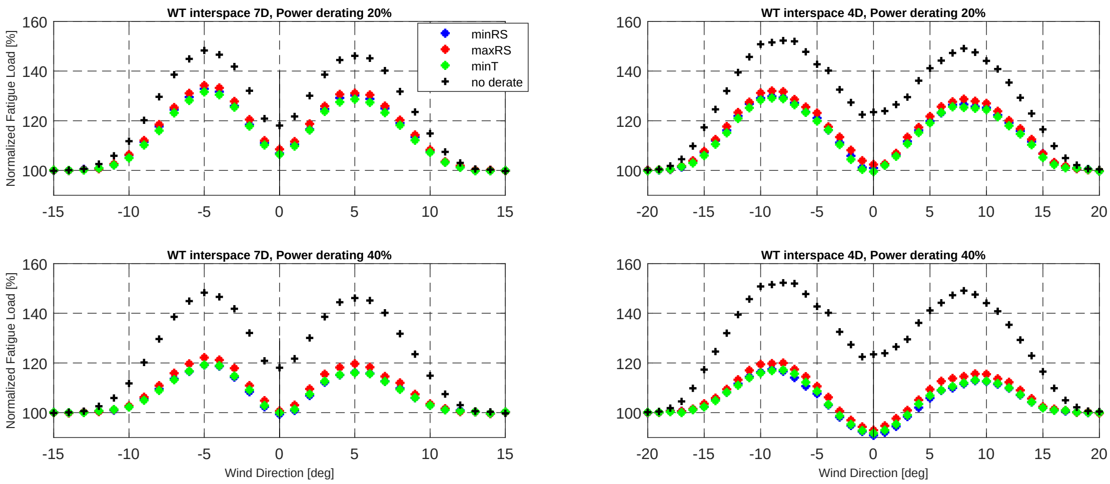

Figure 5. Equivalent 1Hz fatigue tower base fore-aft BM at 8 m/s free wind speed. The loads are normalized by the wake free WT loads at the same wind speed.

affected by the difference between the blade load components normal to the rotor plane. These in every instance either create positive or negative overall yaw moment due to wake meandering and as a result different load patterns between 7D and 4D interspace cases. Especially at small interspace (4D) the overall increase in load levels is higher.

Next are illustrated the equivalent 1Hz fatigue blade root BM, tower base fore-aft BM and nacelle bearing yaw moment from the load analyses (Figures 7, 8, 9) at 16 m/s free wind speed (above rated).

The minRS and minT control strategies return the lowest fatigue loads for most of the examined cases up to ± 10 deg wake angles. Especially for the cases with smaller WT interspace and larger down-regulation factor the blade and nacelle yaw load levels minimized when minRS strategy is applied. However the load pattern for the tower and blade loads change from two humps at tight interspace (4D) to one hump at 7D. This is due to the fact that the downstream

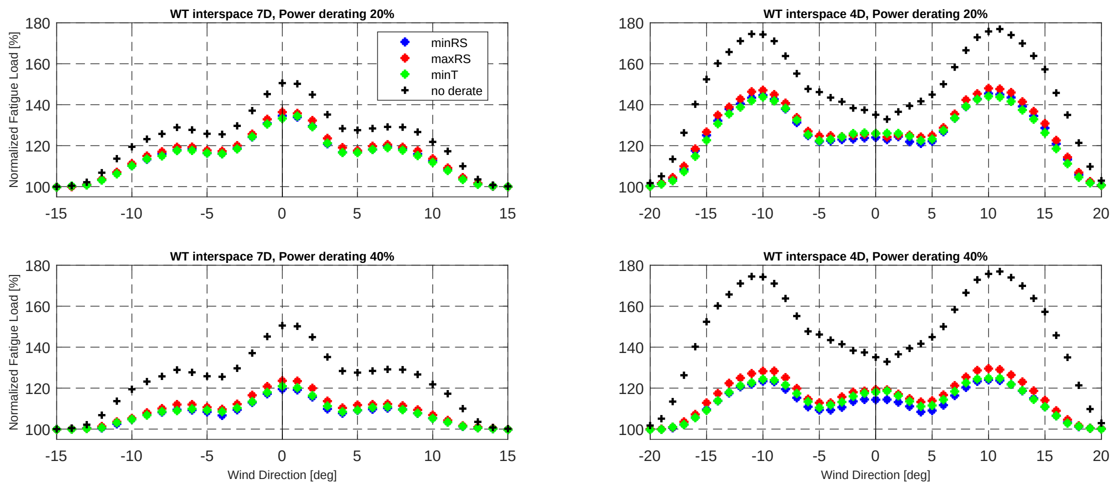

Figure 6. Equivalent 1Hz fatigue nacelle bearing yaw moment at 8 m/s free wind speed. The loads are normalized by the wake free WT loads at the same wind speed.

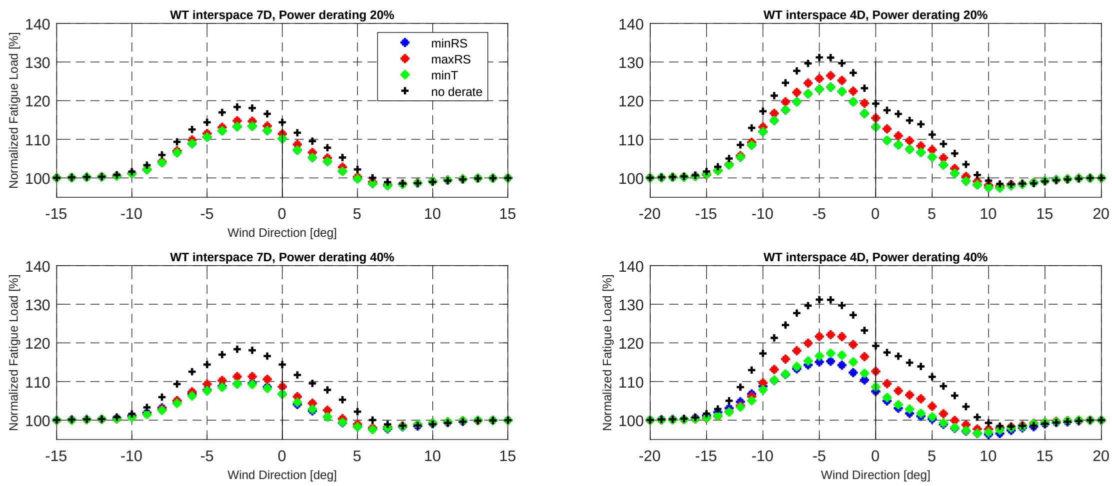

Figure 7. Equivalent 1Hz fatigue blade root flapwise BM at 16 m/s free wind speed. The loads are normalized by the wake free WT loads at the same wind speed.

WT at 16m/s wind speed (above rated) reaches the rated power when the upstream WT is derated. This combined with the full wake situation at 0 degree wind direction returns the highest loads at 0 degree. Again the asymmetric load pattern between positive and negative wind directions which is mainly seen in blade loads is due to the interaction with half-wake deficit and the tilt angle of the downstream turbine.

The loads at 20% curtailment for the minT and minRS control modes are the same (the green and blue dots on the plots overlay) since the operational set-points of rotor speed and pitch angle for both minRS and minT are identical.The normalized blade flapwise fatigue BM is 2.5% higher for the maxRS strategy compared to the other two modes around -4 wind direction for the 7D interspace and 20% derating case. For the tight interspace and 40% derating case at -4 deg wake angle and the maxRS normalized load is 7% and 5% higher compared to the minRS and minT results.

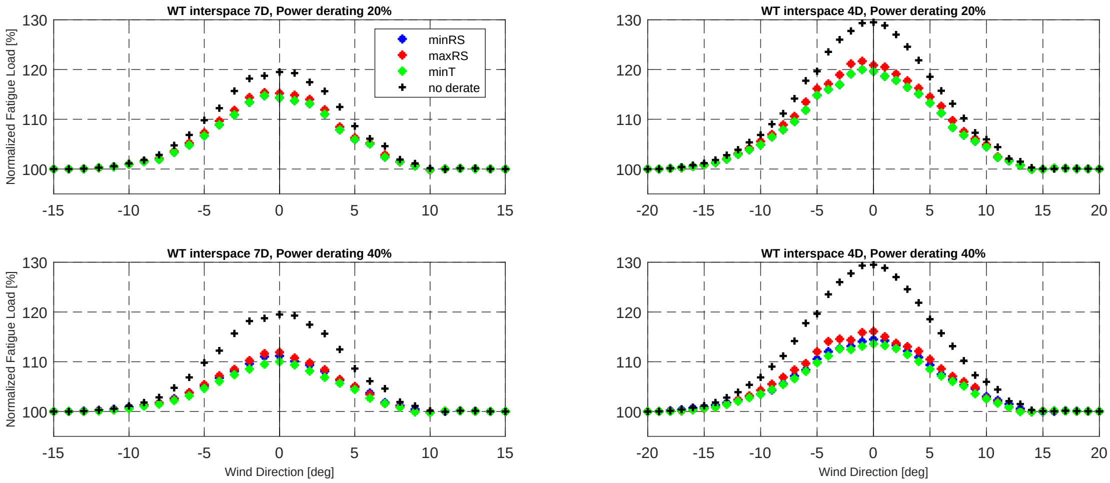

Figure 8. Equivalent 1Hz fatigue tower base fore-aft BM at 16 m/s free wind speed. The loads are normalized by the wake free WT loads at the same wind speed.

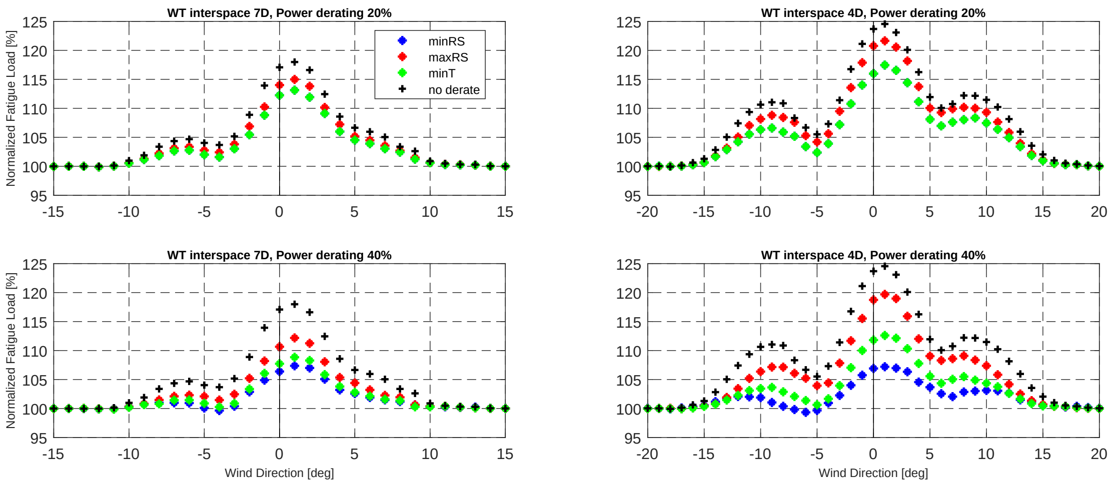

Figure 9. Equivalent 1Hz fatigue nacelle bearing yaw moment at 16 m/s free wind speed. The loads are normalized by the wake free WT loads at the same wind speed.

The wind speeds of the downstream WT are screened in order to investigate further the source of the load variations. The results are showed in Figures 10 and 11 and are normalized by the free stream wind speeds. It can be seen that there is a correlation on the load levels observed above and the wind speed (wake deficit) values. In all cases up to around ± 10 degrees incoming wind direction the deficit from the maxRS control strategy is higher and the load levels follow the same trend. This is an important outcome and links the control strategies directly to the deficit strength due to the upstream WT operation. As the derating factor increases the wind deficit becomes smaller while as the interspace decreases the deficit becomes wider and larger.

The outcomes of the impact of the derating control strategies to the WT loads have important consequences concerning the wind farm operation under curtailment. The WT operation during derating can be such that the wind farm can produce the total demanded power while also

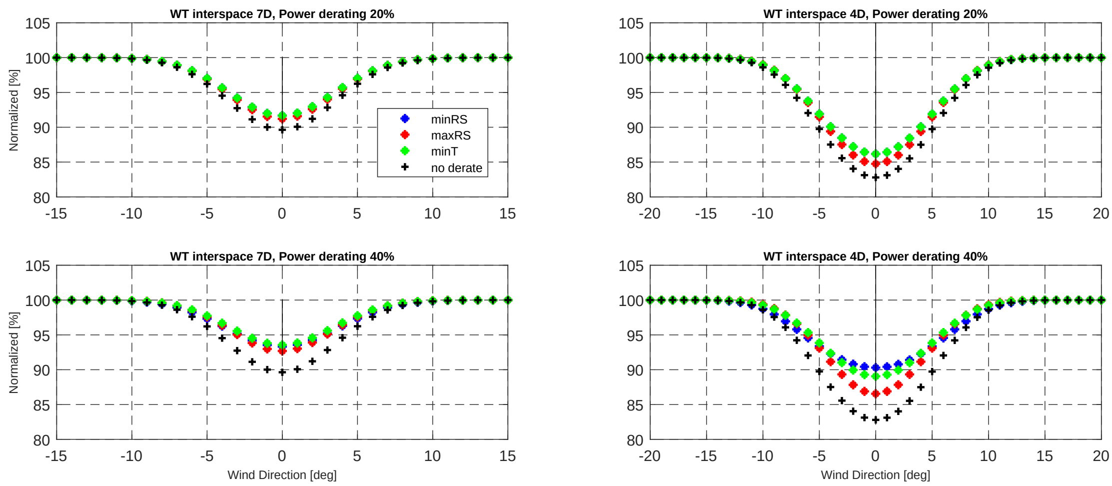

Figure 10. Wind speed seen at downstream WT hub-height normalized with the ambient 8 m/s wind speed.

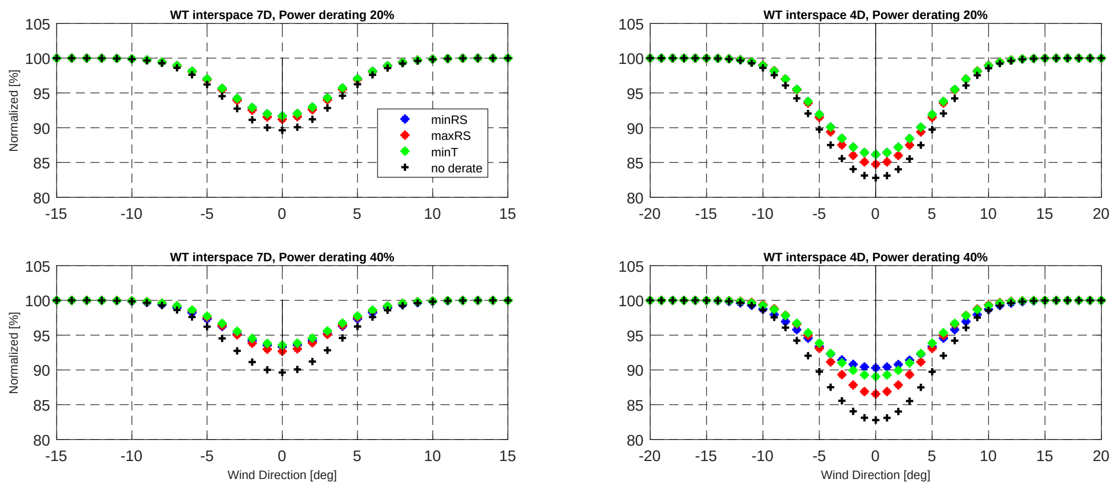

Figure 11. Wind speed seen at downstream WT hub-height normalized with the ambient 16 m/s wind speed.

minimize the fatigue loads per individual WT. This potential of fatigue load mitigation during turbine down-regulation operation by choosing the optimum control strategy is aligned with the findings of Kanev et al study [2]. The followed wind farm control strategies become even more important for wind farms with tighter interspace as the wake impact on loads is higher.

5. Conclusions

Different control strategies for WT power curtailment and their effect to WT component fatigue loads are evaluated. They are based on aeroelastic simulations and the results reveal that the selected strategy affects the WT wakes and consequently the downstream WT fatigue loads. The fatigue loads are driven by the variation of the incoming wind speed and the wake deficit can be altered based on the control strategy. This is an important outcome and links the control strategies directly to the deficit strength due to the upstream WT operation. Especially on this case study the fatigue loads on the blade root, the tower base and the nacelle yaw bearing are lowest when the upfront WT is derated by operating at the minRS and minT strategies for incoming wind directions of up to ± 10 degrees. This means that some of the turbine components would be able to survive longer by choosing the optimal control strategy. This work contributes to the design of the next generation of wind farm controllers where emphasis is given both on the desired WT power derating but also to load alleviation.

Acknowledgments

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References

[1] Gebraad, P. M. O., and van Wingerden, J. W. Maximum Power-Point Tracking Control for Wind Farms. *Wind Energy* (2015).

[2] Kanev, S. K., Savenije, F. J., and Engels, W. P. Active wake control: An approach to optimize the lifetime operation of wind farms. *Wind Energy* (2018).

[3] Larsen, T. J., and Hansen, A. M., 2007. How to HAWC2, the users manual, DTU R-1597(en) Technical report.

[4] Larsen, T. J., Larsen, G. C., Madsen, H. A., and Petersen, S. M. Wake effects above rated wind speed. An overlooked contributor to high loads in wind farms. *Scientific Proceedings. Ewea Annual Conference and Exhibition* (2015), 95–99.

[5] Larsen, T. J., Larsen, G. C., Madsen, H. A., Thomsen, K., and Markkilde, P. S. Comparison of measured and simulated loads for the Siemens SWT 2.3 operating in wake conditions at the Lillgrund Wind Farm using HAWC2 and the dynamic wake meander model. *EWEA Annual Conference and Exhibition* (2015).

[6] Larsen, T. J., Madsen, H. A., Larsen, G. C., and Hansen, K. S. Validation of the dynamic wake meander model for loads and power production in the Egmond aan Zee wind farm. *Wind Energy 16*, 4 (2013), 605–624.

[7] Madsen, H. A., Larsen, G. C., Larsen, T. J., Troldborg, N., and Mikkelsen, R. F. Calibration and Validation of the Dynamic Wake Meandering Model for Implementation in an Aeroelastic Code. *Journal of Solar Energy Engineering 132*, 4 (2010), 041014.

[8] Mirzaei, M., Göçmen, T., Giebel, G., Sørensen, P. E., and Poulsen, N. K. Turbine Control Strategies for Wind Farm Power Optimization. *Proceedings of 2015 American Control Conference* (2015), 1709–1714.

[9] Mirzaei, M., Soltani, M., Poulsen, N. K., and Niemann, H. H. Model based active power control of a wind turbine. *Proceedings of the American Control Conference* (2014), 5037–5042.

[10] Park, A. J., Kwon, B. S., and Law, A. K. Wind Farm Power Maximization Based On A Cooperative Static Game Approach. *Proceedings of the SPIE Active and Passive Smart Structures and Integrated Systems Conference* (2013).

[11] Schaak, P. Heat & Flux - Enabling the Wind Turbine Controller. *European Wind Energy Conference and Exhibition* (2007), 2, 1134–1140.